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The NEAR Solar Conjunction Experiment

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Abstract

The Near Earth Asteroid Rendezvous (NEAR) spacecraft was occulted by the solar disk on February 19, 1997. During the period between February 7 and March 3, 1997, the NEAR X-band telecommunications system was used to carry out a combination of engineering and radio science measurements through the solar corona. This paper reports on the engineering results of that experiment. Statistics on the uplink command acceptance rate and downlink frame error rate are presented as a function of spacecraft position relative to the Sun. In addition, representative open-loop receiver data are presented to characterize the amplitude fading environment encountered during the experiment. Recommendations are given for future solar conjunction events, particularly in the area of ground receiver optimization. The experimental results in this paper provide a unique data set useful for the design of future planetary missions.

Introduction

On its journey to the asteroid 433 Eros, the Near Earth Asteroid Rendezvous (NEAR) spacecraft passed directly behind the Sun on February 19, 1997. Over the wider period of February 7 to March 3, 1997, the X-band downlink signals from the spacecraft were monitored via the Deep Space Network (DSN) to characterize the effect of plasma-induced amplitude and phase scintillations on radio link performance. The results of this experiment have produced a unique data set that, when properly extrapolated, could prove very useful in the design of future planetary missions.

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An inherent characteristic of many planetary missions is that the trajectory design eventually brings the spacecraft into conjunction with the Sun as viewed by an Earth observer. In the periods just before and just after occultation, communications problems occur due to the noise temperature of the Sun and, in the case of superior conjunction (spacecraft beyond the Sun), amplitude and phase scintillations caused by the turbulent solar corona. Preliminary studies of the solar conjunction radio link problem have either focused on Doppler tracking¹ or been mainly analytical in nature.²

Solar conjunction effects are of particular interest to NASA's Solar Probe mission, which will fly a trajectory that brings it over the west limb of the Sun at a distance of 4 solar radii ($4 R_{\odot}$) from the solar center. That mission, currently in the conceptual planning stage, has been studied for many years³⁻⁶ and presents significant challenges in all engineering disciplines. In the spacecraft telecommunications area, the most driving requirement is to capture critical science data in real time as the spacecraft makes its close flyby of the Sun. In addition to Solar Probe, other mission sets such as NASA's Discovery and New Millennium programs also share concerns regarding the radio link performance whenever the Sun-Earth-probe (SEP) angle is less than about 2 degrees.

The NEAR Solar Conjunction Experiment combined engineering and radio science measurements to characterize command and telemetry link performance during solar conjunction. The only other known documentation of X-band telecommunications performance during solar conjunction is a report from the Magellan mission.⁷ Our paper provides statistics on the uplink command acceptance rate that complement the data presented in the Magellan report. More importantly, our paper presents first-of-a-kind statistics on the downlink frame error rate during solar conjunction. Open-loop receiver recordings are also presented that capture the downlink amplitude fluctuations. These measurements should permit a more realistic future analysis of solar conjunction communications effects than has been possible in the past. In addition, the need to determine optimal ground receiver settings for future solar conjunction events is identified.

Experiment Geometry and DSN Coverage

During the solar conjunction period, the NEAR spacecraft traveled in a trajectory that brought it directly behind the Sun. The spacecraft was in a heliocentric orbit at a distance of 3.17 astronomical units (AU) from the Earth and 2.18 AU from the Sun. Figure 1 illustrates the solar conjunction geometry as viewed from Earth as well as the DSN coverage for the experiment. In this figure, "closest approach distance" is the distance (expressed in solar radii) between the center of the Sun and the spacecraft-Earth line in a direction perpendicular to that line. It represents closest distance between the center of the Sun and the path traversed by the radio waves from the NEAR spacecraft. The closest approach distance (d) and SEP angle (θ) are related by $d = 214.9 \sin(\theta)$.

Spacecraft and DSN Radio Frequency (RF) Configuration

For the solar conjunction experiment, the NEAR spacecraft was in an Earth-pointing orientation using its 1.5-meter diameter high gain antenna (HGA) for communications. There were no known spacecraft attitude dynamics that would have affected the results. The telecommunications system incorporated the same basic transponder and command detector unit (CDU) designs as those flown on the Cassini and Mars Pathfinder missions. Tables 1 and 2 list the pertinent uplink and downlink parameters for the experiment, respectively.

In the DSN ground stations, Block V receiver systems were used for downlink telemetry reception. After the signal was downconverted to an intermediate frequency, these systems sampled it and performed the carrier tracking, subcarrier tracking, bit synchronization, and data detection using digital signal processing techniques. For the NEAR Solar Conjunction Experiment, the Block V carrier tracking loop bandwidth (B_L) was set to 10 Hz and the automatic gain control (AGC) loop bandwidth was set to 1.0 Hz. The subcarrier tracking loop (when used) and symbol tracking loop bandwidths were both set to $B_L = 0.5$ Hz. After passing through additional DSN baseband processing equipment, the recovered downlink telemetry was delivered to the NEAR Mission Operations Center (MOC) in Laurel, Maryland. The telemetry data, along with receiver indicators such as lock status and signal strength, were recorded in the MOC for subsequent analysis.

In addition to the Block V receiver systems, the DSN open-loop radio science receivers were used for the experiment. The received carrier signal was downconverted from 8.4 GHz to a few kilohertz and sampled in an operator-selected bandwidth. To keep the carrier signal within the selected bandwidth, these receivers were tuned continually during a pass using a file of predicted downlink frequencies. The digitized data were then written to 8-mm tape for archiving. The resulting tapes, archived by the Radio Science Group at the Jet Propulsion Laboratory (JPL), can be post-processed with a software phaselock loop or a series of fast Fourier transforms (FFTs).

Although radiometric data such as Doppler and ranging measurements were also recorded as part of the experiment, they are not the emphasis of this paper. These data, taken over the period February 7 to March 3, 1997, have been archived by the Radiometric Data Conditioning Team at the Jet Propulsion Laboratory.

Uplink Command Performance

All commanding during the solar conjunction period was done at the 125 bps data rate. A log was kept to record the success rate of the commands versus SEP angle, with the results shown in Table 3. The reader is cautioned that a *statistically small* number of commands was sent during the experiment period. In addition, a command detector unit (CDU) anomaly unrelated to solar conjunction may have caused the first command into the spacecraft to be rejected on several occasions.[‡] There is no way to determine conclusively if rejection of the first command on these occasions was due to the CDU anomaly or the solar environment. For information purposes, the CDU loop bandwidth and AGC time constant were 19.68 Hz and 2.11 sec., respectively, at the 125 bps data rate.

It is worth noting that the command data margin in the absence of solar effects was extremely strong (29 dB) and that solar noise entering the high gain antenna would have reduced that margin by only 2 dB. Based upon this information and prior work⁸, it is believed that the command degradation at low SEP angles was caused mainly by scintillations and not by solar noise.

Downlink Telemetry Performance

The results in Table 4 describe the downlink telemetry performance during several opportune periods of the experiment. All the data were obtained during one-way downlink operation using the Block V receiver. The data show the downlink performance at 1104 bps to be highly reliable at an SEP angle of 2.3° ($d = 8.6 R_s$). However, at an SEP angle of 1.1° ($d = 4.1 R_s$), the performance was very poor, with only 3% of the received frames being correctable. Surprisingly, the performance using 39.4 bps data was not any better, with 0% of the received frames being correctable at an SEP angle of 1.1° ($d = 4.1 R_s$). The carrier and symbol lock indications from the Block V receiver indicated that these loops were in lock during all the periods indicated in Table 4.

The cause for the relatively poor performance of the 39.4 bps data at lower SEP angles is presently not well understood. Two possible explanations are: (1) despite a large increase in bit energy relative to the 1104 bps data, the 39.4 bps data may have been susceptible to occasional deep amplitude fades because of its longer frame time (4 minutes versus 8 seconds) and (2) rapid amplitude scintillations in the downlink signal may have disrupted the operation of the carrier tracking loop. With the Block V receiver set for a relatively narrow AGC loop bandwidth (1.0 Hz), the higher frequency

[‡]This anomaly has also been observed on the Mars Pathfinder mission. Apparently, the CDU is dragged off of its nominal center frequency due to a beat note generated by the frequency sweep used to acquire the transponder. As a result, the first command is occasionally rejected because the CDU is being pulled back to its nominal center frequency during the command period.

content of the amplitude scintillations would have been converted into excess phase error instead of being tracked out by the receiver. This mechanism would have affected the performance at both bit rates.

The column labeled "frames received at MOC" in Table 4 does not include any frames that were transmitted by the spacecraft but never arrived at the MOC. These are included in the column entitled "missing frames." There are many reasons why a frame might be missing, including poor quality due to scintillations, equipment problems at the DSN, and/or equipment problems at the MOC. These frames have not been incorporated into the data other than to simply list them in a column.

It was found that the downlink telemetry performance in two-way mode was generally worse than the performance in one-way mode at lower SEP angles. This was, presumably, a result of increased spectral broadening of the downlink carrier. For example, on day-of-year 048 at an SEP angle of 1.1° ($d = 4.1 R_s$), occasional correctable frames at 1104 bps were being received in one-way mode. However, when two-way communications were initiated, all the frames became uncorrectable. At that time, the carrier tracking loop bandwidth was increased temporarily from 10 to 50 Hz in an attempt to improve the performance. However, this action caused carrier lock to be promptly lost. On day-of-year 052 at an SEP angle of 1.3° ($d = 4.9 R_s$), occasional correctable frames at 39.4 bps were being received in one-way mode. However, when two-way communications were again initiated, all the frames again became uncorrectable.

The previous observations lead us to conclude that the Block V receiver settings, although adequate for higher SEP angles, were not adequate for lower SEP angles. However, it is not clear that widening of the carrier tracking and AGC loop bandwidths would have significantly improved performance. For future solar conjunction events, the scintillation environment needs to be better characterized so that more optimal receiver settings can be determined. The open-loop receiver recordings that have been archived as part of this experiment should prove useful for that purpose. The tapes can be analyzed in more detail to determine amplitude and, possibly, phase noise spectra as a function of SEP angle. In addition, the signals on the tapes might be used to re-create the NEAR solar conjunction environment in the laboratory. With this capability in place, end-to-end link testing can be accomplished to determine the best Block V receiver settings for a given bit rate. Once these settings are determined, then the appropriate amount of spacecraft transmitter power can be allocated to establish a reliable downlink for future solar conjunction events.

Open-Loop Receiver Measurements

Open-loop receiver recordings were made whenever possible during the solar conjunction period. These recordings, when sufficiently processed, capture the dynamics of the downlink signal without the effects of receiver phaselocking. Sample recordings have been processed to give the reader an idea of the amplitude scintillation environment encountered (Fig. 2). Each plot is a series of FFT results computed once per second and presented relative to the mean signal strength for that time period. For a closest approach distance of $4.1 R_s$ (the region of interest for the Solar Probe mission), Figure 2c indicates fades up to 15 dB.

Conclusions

The NEAR Solar Conjunction Experiment has provided a baseline set of data for the performance of the NEAR X-band telecommunications system during solar conjunction. For the NEAR mission conditions, the downlink performance was good at an SEP angle of 2.3° ($d = 8.6 R_s$), but poor at an SEP angle of 1.1° ($d = 4.1 R_s$). At the 1.1° SEP angle, the performance was poor at both the 1104 bps and 39.4 bps bit rates. The precise cause of the poor performance at 39.4 bps is unknown, but may be related either to the longer frame time or excessive phase noise in the ground receiver carrier tracking loop.

A significant observation made during the experiment was that the ground receiver settings were potentially non-optimal for the environment encountered at low SEP angles. The receiver settings must be carefully optimized to handle the expected amplitude and phase scintillations in the weak signal strength environment of a deep space mission. For future missions at X-band, optimal receiver settings must be determined so that the proper amount of spacecraft transmitter power can be budgeted to overcome solar conjunction effects. The results of this experiment, when properly extrapolated to other mission conditions, should provide a very useful data set for that purpose.

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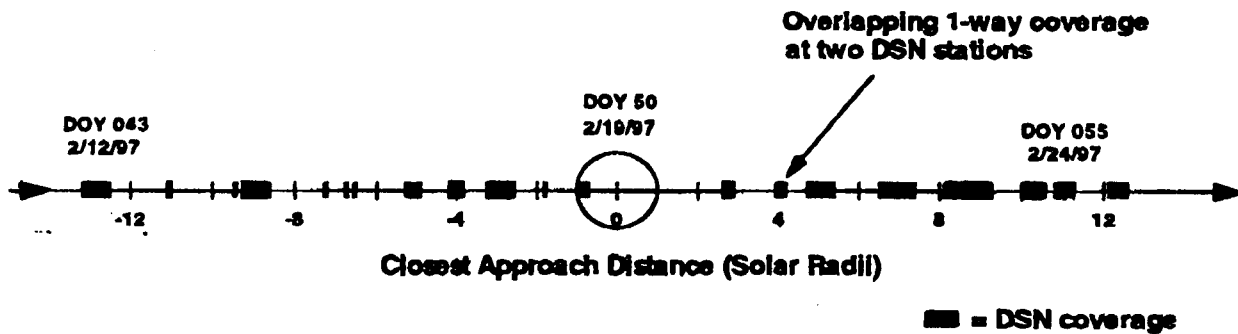
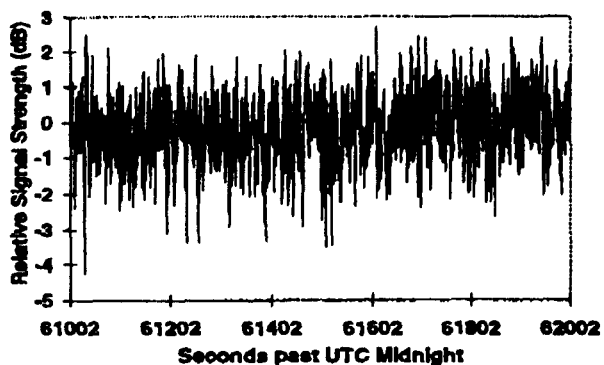
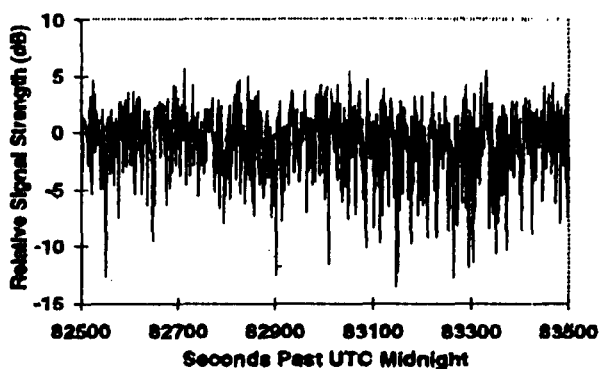


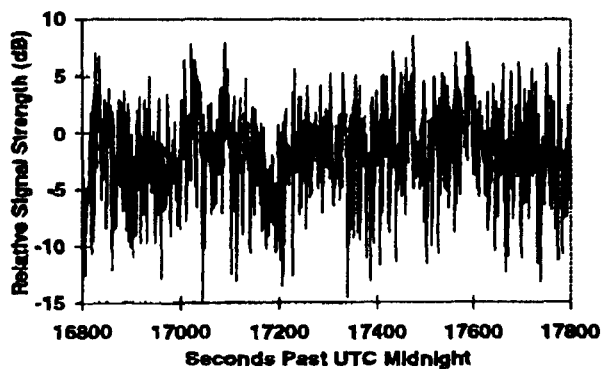
Fig. 1 Spacecraft path during the solar conjunction period as viewed from the Earth. The object in the center represents the solar disk. The arrows represent the direction taken by the spacecraft.



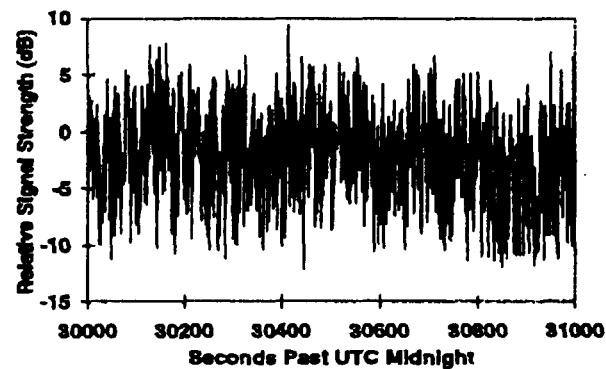
(a) DSS-15, Day-of-year 97-044, SEP angle= 2.9°
Closest approach distance= $11.0R_E$



(b) DSS-15, Day-of-year 97-046, SEP angle= 1.75°
Closest approach distance= $6.5R_E$



(c) DSS-45, Day-of-year 97-048, SEP angle= 1.1°
Closest approach distance= $4.1R_E$



(d) DSS-65, Day-of-year 97-052, SEP angle= 1.1°
Closest approach distance= $4.1 R_E$

Fig. 2 Open-loop receiver data showing carrier signal amplitude fluctuations recorded on several sample days of the experiment. The FFT averaging factor was equal to 1 (no averaging). (DSS= Deep Space Station)

Table 1 NEAR uplink RF telecommunications parameters

Parameter	Value	Notes
Uplink frequency	7181.96 MHz	
Uplink transmit power	20 kW nominal	DSN 34m high efficiency (HEF) antennas
HGA gain	39.2 dBic (right-hand circular)	1.5m-diameter dish
Spacecraft system noise temperature	257 K	At transponder input port. In absence of solar effects
Uplink bit rate	125 bps	On 16 kHz sine wave subcarrier
Uplink command modulation index	1.3 radians peak	
Uplink ranging tone modulation index	0.8 radian peak	Ranging was used only for limited portions of the experiment
Command data characteristics	Commands were sent individually. Each command was 464 bits long including a checkerboard (101010...) preamble of 176 bits and a checkerboard postamble of 80 bits. No idle pattern was used prior to each command.	
Predicted uplink carrier power	-107 dBm (unmodulated) -110 dBm (w/ranging tones)	In absence of solar effects
Predicted uplink P/N ₀ ratio	67 dBHz (unmodulated) 64 dBHz (w/ranging tones)	In absence of solar effects
Predicted uplink command margin	32 dB (w/o ranging tones) 29 dB (w/ranging tones)	In absence of solar effects

Table 2 NEAR downlink RF telecommunications parameters

Parameter	Value	Notes
Downlink frequency	8438.09 MHz (coherent) 8435.37 MHz (noncoherent)	
Spacecraft transmit power	3.5 W	At antenna port (after passive losses)
HGA gain	40.2 dBic (right-hand circular)	1.5m-diameter dish
Ground system G/T ratio	52.6 dB/K	DSN 34m HEF antennas
Downlink-bit rate	1104 and 39.4 bps prior to Reed-Solomon coding 1262 and 45 bps after Reed-Solomon coding	
Downlink telemetry modulation index	1.2 radians peak (1104 bps data) 0.9 radian peak (39.4 bps data)	
Downlink ranging modulation index	0.3 radian peak	Ranging was used only for limited portions of the experiment
Downlink coding	CCSDS compatible convolutional rate $\frac{1}{2}$, k=7 with Reed-Solomon (255,223) coding. Interleaving depth=5.	
Telemetry data characteristics	The high-rate data (1104 bps) was modulated directly onto the carrier in biphase-L format. The low-rate data (39.4 bps) was modulated onto a 23.4 kHz subcarrier in NRZ-L format.	
CCSDS frame length	10,112 bits, which included 8800 information bits, 1280 Reed-Solomon parity bits, and 32 sync marker bits.	
Predicted downlink carrier power	-151 dBm modulated (1104 bps) -146 dBm modulated (39.4 bps)	In absence of solar effects
Predicted downlink P_r/N_o ratio	32 dBHz (1104 bps) 37 dBHz (39.4 bps)	In absence of solar effects
Predicted downlink telemetry margin	6 dB (1104 bps) 19 dB (39.4 bps)	In absence of solar effects

Table 3 Uplink command performance data

Day of year	Nominal SEP angle	Commands sent	Commands received	Notes
038	6.2°	34	34	
041	4.5°	8	8	
043	3.5°	8	7	First command was missed. May have been due to a CDU anomaly. First command was missed. May have been due to a CDU anomaly.
045	2.4°	8	7	
048a	1.1°	8	2	
048b	0.8°	14	1	
051	0.7°	22	1	
052	1.3°	8	3	
055	2.9°	6	6	
057	3.9°	4	3	First command was missed. May have been due to a CDU anomaly.
059	5.0°	8	8	

Table 4 Downlink telemetry performance data^a

Date	Day of year	Time (UTC)	DSN station	SEP angle	Closest approach distance (R ₀)	Bit rate (bps)	Frames received at MOC	Correctable frames	Uncorrectable frames	Missing frames
2/12/97	043	20:39-23:46	15	3.4°	12.7	1104	1400	1400 (100%)	0	0
2/14/97	045	20:20-22:00	15	2.3°	8.6	1104	749	747 (99.7%)	2	2
2/17/97	048	04:01-05:05	45	1.1°	4.1	1104	320	9 (3%)	311	161
2/21/97	052a	08:28-09:31	65	1.1°	4.1	39.4	13	0 (0%)	13	3
2/21/97	052b	16:30-17:18	15	1.3°	4.9	39.4	13	7 (54%)	6	1
2/24/97	055	21:58-00:40	15	3.0°	11.2	1104	1215	1215 (100%)	0	0

^aAll data were taken during one-way downlink operation.